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Three-Dimensional Finite-Difference Thermoregulatory Model of a Squirrel Monkey

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16. ABSTRACT

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● *Original Contribution*

A THREE-DIMENSIONAL FINITE-DIFFERENCE THERMOREGULATORY MODEL OF A SQUIRREL MONKEY

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A three-dimensional thermoregulatory model of a squirrel monkey, whose shape is approximated by 742 rectangular blocks of varying sizes, has been developed. The inhomogeneous model has four layers: a core, a composite layer of muscle and fat, skin, and fur. The model simulates the flow of heat into and out of the body, including internal heat generation (metabolism) by the body, cooling and distribution of heat by blood, thermal conduction throughout the body, evaporative heat loss from sweating, and radiation and convection from the outer surface of the body. It also simulates dynamic thermoregulatory behavior such as peripheral vasomotor responses (skin vasodilation and vasoconstriction) and variable sweating rates. Computed results are compared with available experimental data; the agreement is good, especially for ambient temperatures above 26°C.

Model, Thermal, Squirrel monkey, Finite-difference.

INTRODUCTION

Increased usage of radiofrequency (RF) radiation has necessitated the development of predictive models to quantify both the absorption of RF energy and the resulting thermal response of the human body. Such models are indispensable for safe application of RF fields for therapeutic purposes or for the determination of hazardous field levels emitted by a radiating device. However, the development of realistic models through computer simulation is difficult because of the extremely complicated absorption patterns produced by RF fields. This requires three-dimensional thermal response models with high spatial resolution capabilities.

Whereas existing human thermoregulation models[6] can be adapted to investigate the thermal interaction with RF fields, their predictive accuracy should be viewed with apprehension because these models have been reasonably validated only for more conventional environmental heat sources (ambient temperature and exercise). Because RF energy has the potential to produce localized temperature increases, so-called "hot-spots," without any significant increase in a single measure of core temperature, it is difficult to undertake human experimentation to validate a model. Therefore, to achieve experimental verification of a model, and minimize risk of human experimentation under RF exposure conditions, an acceptable approach is to model an animal whose thermoregulatory system is similar to man's and then perform the necessary thermophysiological experiments on the animals. The verification of such an animal model based on these measurements would furnish substantial support for a similar human model.

We have chosen a squirrel monkey as a surrogate to study the accuracy of the thermal response models. With the exception of their tail, the squirrel monkey has a shape similar to man, and they, like man, are a sweating, nonpanting primate whose major route of heat loss is from the outer surface of the body. However, they do not sweat over the entire body surface, but sweat primarily on the

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palms of the hands and soles of the feet.[11] In addition, their tail is a very effective heat dissipator, a mechanism not available to man.

This paper describes a three-dimensional finite difference thermoregulatory model of a squirrel monkey; the main objective is to demonstrate that a satisfactory model can be achieved by the utilization of existing physiological data and the adaptation of a human model. The analysis represents a comprehensive attempt to realistically configure the geometry of an animal during thermal interaction with the environment. The model considers active mechanisms of thermoregulation such as vasodilation, vasoconstriction, and sweating, as well as the passive modes of heat transfer (conduction, convection, and radiation). The method is general and can predict temperature distributions in complex spatial geometries in which metabolic rates and blood flow rates can vary with tissue type and with time. When possible, calculated values are compared with experimental data.

METHODS AND MATERIALS

Thermoregulatory model

Figure 1 illustrates, in block diagram form, the basic components needed to study human thermoregulation. The thermoregulatory system consists of two major parts: an active or controlling system and a passive or controlled system. The controlling system consists of a hypothalamic controller in the brain and associated afferent and efferent pathways. This controller receives afferent signals from thermoreceptors in the skin and body core, integrates this temperature information, compares the results with set point temperatures, and produces the appropriate alteration in vasomotor response, sweating, or shivering via efferent pathways. Note, that these thermoreceptors are either "warm" or "cold" receptors. Upon sudden warming, a "warm" receptor will produce electrical impulse signals that are carried by neural pathways to appropriate locations. A decrease in the production of signals occurs when the area is suddenly cooled. A "cold" receptor acts in the opposite fashion; it increases the production of signals when a drop in the local temperature occurs. The controlled heat transfer system represents the passive modes of heat transfer (conduction, convection, and radiation) within and from the surface of the body.

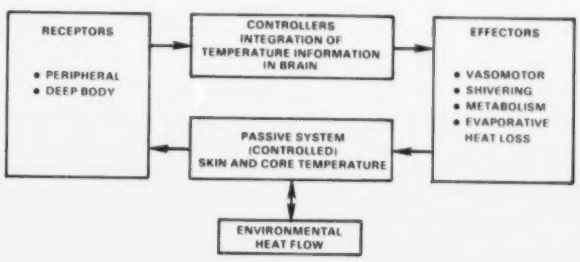


Fig. 1. Block diagram of the basic thermoregulatory system.[3]

Using the same general approach as a human model,[15] the engineering or physical model for the monkey's thermoregulatory system will, therefore, consist of two major parts: a controlling system and a controlled system. The controlled system is modeled by a transient heat conduction model, with the controlling system providing physiologically relevant thermal boundary conditions to maintain homeothermy. The controlling system incorporates set point or reference temperatures as the preferred body temperatures. The mathematical simulation attempts to maintain those set point temperatures by calculating the deviation between the set point temperatures and the actual body temperatures. This deviation represents an error signal; the magnitude of the response is directly related to the size of the error signal.

Controlled system

The controlled system is a transient heat conduction model which includes internal heat generation and heat dissipation. The internal heat generation results from body metabolism. The internal heat dissipation occurs by convective exchange with the cardiovascular system and a combined convective and radiant exchange with the surrounding environment at the surface of the skin and respiratory tract.

To solve the heat transfer equation for the squirrel monkey, a model was constructed from 742 rectangular blocks of varying sizes. The model utilizes rectangular blocks to configure the geometry of the animal primarily because the future use of this model will be in conjunction with an RF deposition model. Heat transfer analyses allow for more realistic block treatment, but currently available RF deposition models do not.[10] The model represents a spatial approximation of a 1.2 kg monkey in a sitting position because the heat transfer calculations will be compared to experimental exposure data for an animal in this position. Table 1 lists the volume, weight, and fraction of the total volume of the body for the various regions of the model. The size and shape of the various parts of the monkey's body were determined from measurements on a monkey. Because of difficulties in ap-

Table 1. Regional tissue distribution by weight, volume, and fractional volume

	Weight g		Volume cm^3		Fraction by volume	
Region	Core	Outer	Core	Outer	Core	Outer
Feet	22.8	28.3	13.4	27.5	0.33	0.67
Legs	92.6	183.7	55.1	177.7	0.24	0.76
Trunk	184.0	329.9	113.6	315.0	0.27	0.73
Head and neck	118.5	39.9	69.7	38.8	0.64	0.36
Arms	56.4	120.9	33.2	117.5	0.22	0.78
Hands	6.5	10.6	4.1	10.0	0.29	0.71
Tail	34.4	34.4	11.1	42.5	0.21	0.79
Total	515.2	747.7	300.2	729.0	—	—

proximating the curved portions of the monkey's body with rectangular blocks, the surface area in relation to body weight is 12% larger in this model than the average value reported by others.[13] The surface area of the tail is 13% of the total surface area; this value is 2% larger than that reported by Stitt *et al.*[13]

Figure 2 illustrates the block model. Note that it contains four distinct types of material: a core, an outer layer, skin, and fur. The core of the torso and head is comprised of viscera, skeleton, and connective tissue, whereas the core of the arms, hands, legs, feet, and tail is composed of skeleton and connective tissue. The outer layer is a composite layer of muscle and fat. Because detailed anatomical information for squirrel monkeys is lacking, the tissue distribution and the fractional volume for the core and outer layers are based on information described by Stolwijk[15] for his human model. The tail's core (skeleton) and outer layer (connective tissue) were partitioned from a visual inspection of a cross-sectional photograph of the tail.[12] Because the thickness of the skin layer is very small, it was assumed to have zero thickness for modeling purposes. How these volumes with no mass are handled in the heat transfer calculations is described below. The fur was included in the model as a uniform layer, 0.32 cm thick, that covered the entire surface of the animal except such regions as the palms of the hands, soles of the feet, and areas around the eyes and nostrils.

The finite-difference solution is achieved by representing the mass of each rectangular block of Figure 2 by a node which is placed in the center of the block. The paths for heat flow between the nodes are represented by heat conductors that are connected to the nodes. The thermal energy of each node is represented by a capacitor whose value is the amount of heat required to raise the temperature of the mass 1°C. Thus, the problem is reduced to a thermal network where the temperature of each node is determined by solving the following finite difference equation:[5]

$$(C_i/\Delta t)(T_i^{m+1} - T_i^m) = \sum_j K_{ij}(T_j - T_i)^m + Q_i \quad (1)$$

where

$C_i = \rho c \Delta V$ = thermal capacitance of node i,
ρ = density of tissue,
ΔV = volume of block associated with node i,
c = specific heat of tissue,
Δt = time interval,
K_{ij} = conductor for conduction, convection, or radiation,
$K_{ij} = kA/\Delta d$ = conductor value for conduction,
A = cross-sectional area perpendicular to the direction of heat transfer,
k = thermal conductivity of tissue,
Δd = distance between nodes of the conductor,
$K_{ij} = hA$ = conductor value for convection,
h = convective heat transfer coefficient,
K_{ij} = conductor for radiation = $\sigma AF(T_j^2 + T_i^2)^m \times (T_j + T_i)^m$
σ = Stefan-Boltzman constant,
F = geometrical "view" factor,
Q_i = heat sources (metabolic and evaporation),
T_i^m = present temperature of node i, and
T_i^{m+1} = future temperature of node i.

From knowledge of the surface area, the volume, and the tissue composition of each block, values can be determined for the conductors associated with conduction, convection, and radiation. Further, when Equation (1) is rearranged so that all the terms involving the present temperatures (level m) are on the same side of the equation, then

$$T_i^{m+1} = T_i^m + (\Delta t/C_i)S \quad (2)$$

where S is a composite term that contains all those individual terms on the right hand side of Equation (1). Thus, Equation (2) is an explicit expression that calculates new temperatures from old temperatures. The successive application of the formula at each node yields the new temperatures at every node in the network. This can be repeated until steady-state conditions are reached. To insure stability of the solution, the time interval Δt must be chosen so that it is less than or equal to the most restrictive value as based on the nodal relation that contains the smallest capacitance and the largest total conductance.[5]

Nodes that represent the skin and fur layers are given special treatment. Namely, because both layers are thin and knowledge of the temperatures inside the layers is not needed, their volume or mass is neglected. On the other hand, calculation of temperatures at the surface of the monkey is important because heat transfer modes such

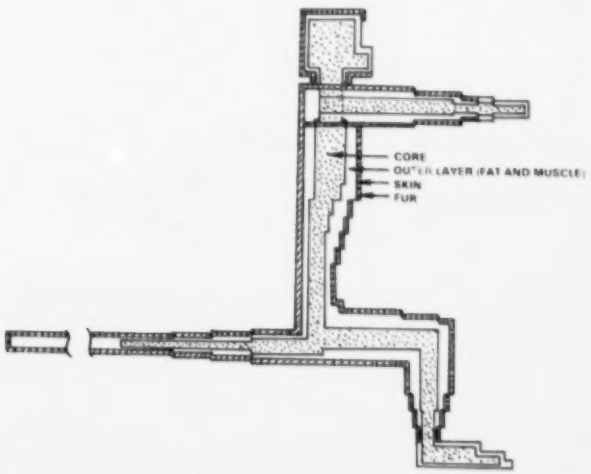


Fig. 2. A side view of the block model of a squirrel monkey in cross section taken through the sagittal plane of the body and the midlines of the arms and legs.

as convection, radiation, and evaporation are directly dependent on surface temperatures. These nodes are, therefore, designated as interface nodes having zero thermal capacitance. Nodal temperatures are calculated by Equation (1) with $C_i = 0$, that is,

$$T_{i+1}^m = (\sum_j K_{ij} T_i^m + Q_i) / \sum_j K_{ij} \quad (3)$$

In other words, the nodal temperatures are determined by assuming the heat that enters each node also leaves it, and consequently the presence of these nodes does not affect the temperatures of those nodes on either side of the interface.

The model also utilizes one node for the central blood pool and one for the external environment.

Figure 3 shows the relationship of the various thermal conductors, thermal capacitors, and heat sources associated with a nodal representation of the four layers of the model. For ease of viewing, only a two dimensional schematic is given, however, the model is three-dimensional. The subscripts C, O, S, and F refer to core, outer layer, skin, and fur, respectively. Thus K_{CO} is a thermal conductor which connects the core and outer layer nodes. The K_{BF} terms designate the amount of heat convectively exchanged by each node and the central blood pool. Heat exchange between the fur layer and surrounding environment by convection and radiation is represented by the conductors K_{CON} and K_R, respectively. The other heat exchange modes include: metabolic heat production, Q_M, and evaporative heat dissipation in the skin (basal and sweating) and respiratory heat loss in the lungs, Q_E. In the thermal network the Q terms represent heat sources (Q_M) and heat sinks (Q_E). With this arrangement, the thermal network, which approximates the controlled thermal system of the squirrel monkey, consists of a total of 1294 nodes connected together by 3954 thermal conductors, 1294 thermal capacitors, and 1364 thermal sources (456 evaporative and 908 metabolic). The transient temperature profile can be calculated for each node, that is, at 1294 interior and surface locations.

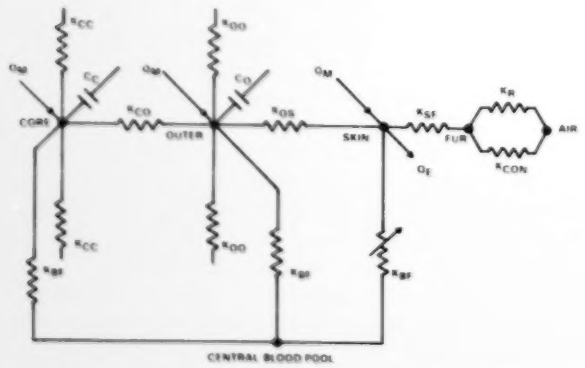


Fig. 3. Two-dimensional view of the thermal network showing the relationship of the various conductors, capacitors, and heat sources associated with a nodal representation of the model's four layers.

Thermal conductors and capacitors. The values for thermal capacitors are obtained from knowledge of the mass or volume and specific heat of the material associated with the nodes that the capacitors are attached to. The specific heats for the different tissues (skeleton, viscera, muscle, and fat) are based on data provided by Stolwijk.[15] For blocks that contain a composition of two tissues, for example, muscle and fat, average specific heats were determined from the distribution of the tissue types by weight.

Interior conductor values (K_{CC}, K_{OO}, K_{CO}, and K_{OS}) are specified according to the thermal conductivity of the tissue type, the cross-sectional area perpendicular to the direction of heat flow, and the conductor length between terminating nodes (see Equation 1). The thermal conductivities for conductors connecting the core and outer layer are computed by performing a weighted average of the two conductivities with respect to conductor lengths. Each interior node is connected to six adjacent nodes by six conductors because there are three cross-sectional areas perpendicular to the direction of heat flow. Interface nodes (skin and fur), on the other hand, have only one plane through which heat can flow, and they are consequently connected by two conductors to adjacent nodes on either side of the interface. The value for K_{SF} is based on the thermal insulation of animal coats.[2]

Conductor values (K_{CON}) for convective heat exchange between the fur surface and the external environment depend on the surface area and the convective heat transfer coefficient (see Equation 1). In lieu of convective heat transfer coefficient values for squirrel monkeys, human data provided by Stolwijk[15] was used. These values are for still air conditions (air flow < 0.1 m/s). Likewise, conductors (K_R) for radiation-links which couple the fur nodes to the external environment are based on radiative heat transfer coefficients obtained from human data.

Conductor values (K_{BF}) for convective heat exchange between each node and the central blood pool depend on the blood flow rates. Basal blood flow rates for the various regions, except the tail, are scaled from human data by comparing cardiac output. There are no data on tail blood flow in the squirrel monkey, hence, tail blood flow rates were scaled from rat tail blood flow information. Because blood flow plays a major role in heat transfer within the body, these terms will be explained further.

Blood flow rates. A marked redistribution of blood flow occurs when primates are heat stressed.[9] In general, the skin blood flow is sharply increased (vasodilation) whereas blood flow to visceral organs and muscle tissue declines or is at basal levels. When the ambient temperature is below the monkey's thermoneutral zone, skin blood flow is reduced (vasoconstriction). Thus, the skin blood flow is highly dependent upon ambient temperature. Active vasodilation, along with increased sweating, represents the body's major adjustment to heat loads.

Utilizing the same approach as that by Stolwijk[14] in the human model, an empirical relation for local skin blood flow is given by the expression

$$BF_i = \frac{[BFB_i + \alpha_i \cdot DILAT]2^{(T_i - T_{i,set})/10}}{1 + \beta_i \cdot STRIC} \quad (4)$$

where

BFB_i = local basal blood flow rate,
T_i = local skin temperature,
$T_{i,set}$ = local skin set point temperature,
DILAT = total controller command for skin vasodilation,
STRIC = total controller command for skin vasoconstriction,
α_i = fraction of DILAT command applicable to the skin of node i, and
β_i = fraction of STRIC command applicable to the skin of node i.

In the equation, the terms DILAT and STRIC are controller equations which will be discussed later (see section on controlling system). The weighted vasodilation command $\alpha_i \cdot$ DILAT is added to the basal blood flow to increase skin blood flow in response to increased body temperatures. The weighted vasoconstriction command $\beta_i \cdot$ STRIC acts to reduce blood flow in response to decreased body temperatures. As will be shown later, the DILAT and STRIC commands are functions of both the integrated skin response and the difference between brain temperature and its set point temperature; however, it is also known that local skin temperature affects blood flow. Therefore, the exponential term in the expression accounts for the local temperature effect. It doubles the blood flow rate for every 10°C increase in local temperature above the set point temperature and cuts the flow in half for a 10°C drop in temperature. Note also that the controller commands DILAT and STRIC do not act simultaneously. If vasodilation occurs, then STRIC = 0; when vasoconstriction takes place, DILAT = 0.

For each major region of the body (head, trunk, arms, hand, legs, and feet), except for the tail, fractional values for vasodilation and vasoconstriction commands (α and β) are distributed in the same proportion as in the human model. The tail is treated separately by arbitrarily assigning the largest value (1.0) for α and β. The rationale for this value is based on the premise that peripheral circulation in the tail is very important for thermoregulation. In fact, the tail may be the single most important organ for vasomotor heat dissipation. Individual values for each skin surface node within a given region are determined by redistributing α_i and β_i in direct proportion to the surface area of each node relative to the surface area of the entire region.

Blood flow in muscle tissue is essentially controlled by the metabolic demand for oxygen. Muscle blood flow is increased when oxygen requirements increase as a result of work activity or shivering. Shivering is initiated when the body is subjected to a sufficiently low ambient temperature (<20°C for a squirrel monkey).[12] However, for this study the muscle blood flow is fixed at basal levels because the thermoregulatory response below an ambient temperature of 20°C is not considered. In addition, the monkey is assumed to be in a sedentary state.

With the exception of the tail, basal blood flow rates, BFB_i, are scaled from the human model by comparing cardiac output. For basal blood flow in the tail, scaled rat data[7] have been applied. Cardiac outputs are 0.1, 0.2, 0.26 ml/(min g) for humans, squirrel monkeys, and rats, respectively.[1] Thus, for the various body regions the squirrel monkey's basal blood flow is increased by a factor of 2 over the human basal levels, whereas for the tail region basal blood flow is decreased by a factor 0.77 below the rat basal level.

Heat sources and sinks. The other heat exchange modes shown in Figure 3 include metabolic heat production, Q_M, and heat loss by sweat evaporation from the skin, Q_E. The body has its own source of heat production by metabolic activity. In muscle tissue, the metabolic rate can be accelerated above basal levels as a result of work activity and shivering. The total metabolic heat production for squirrel monkeys is approximately 6 W/kg in the thermoneutral zone (26–36°C) and increases fairly rapidly for ambient air temperatures below the thermoneutral zone.[12] For lack of better information, the distribution of the metabolic heat production in the various regions (torso, arms, legs, etc.) of the model is proportioned by weight, and then apportioned in each layer (core, outer, and skin) according to the human model. Further, it was assumed that the metabolic rate for the tail was minimal (less than 1% of the total). Within each layer, metabolic heat sources for the individual nodes in the thermal network are determined by distributing the total metabolic rate for that region in proportion to the respective weight of the block that a node represents. There are a total of 908 metabolic heat sources in the thermal model.

Heat lost due to sweating, Q_E, is a major avenue by which the body regulates internal temperatures. It is important to observe from Figure 3 that evaporation takes place from the surface of the skin and not the surface of the fur. The evaporation process was modeled in this fashion because the conduction of water along the fibers of fur is low.[2] Several mathematical models have been proposed to calculate heat loss by sweating. They are all empirical and attempt to give a best-fit to experimental data for various conditions. The equation used by Stolwijk[14] takes the form

$$Q_{E,i} = (QB_{E,i} + S_i \cdot SWEAT)2^{(T_i - T_{i,set})/10} \quad (5)$$

where

$QB_{E,i}$ = basal evaporative heat loss,
SWEAT = total controller command for sweating,

S_i = fraction of sweating command applicable to skin of segment i,
T_i = local skin temperature, and
$T_{i,set}$ = local skin set point temperature.

Note that the general form of this expression is very similar to Equation (4). For a given value of the controller command SWEAT, it is evident that the skin sweats more at a higher local skin temperature than at a lower temperature. As will be explained later, SWEAT is a function of hypothalamic and mean skin temperatures; thus, the local sweating response is both an additive and multiplicative function of the local skin, core, and mean skin temperatures. The quantity S_i accounts for the fact that sweat production is not uniformly distributed over the surface of the body. Since a squirrel monkey only sweats on his feet and hands, S_i, is, of course, zero except for those surface nodes which represent the soles of the feet and the palms of the hands. For lack of better information, we have assumed that the sweat glands are uniformly distributed over these areas. The total basal evaporative heat loss in the thermoneutral zone is about 1 W,[12] and the distribution of QB_E to the various regions of the model is accomplished in the same fashion as with the human model.

There is a maximum rate of evaporation that is possible for a given set of environmental conditions. The expression for the maximum rate of evaporation used in the model[15] is shown below:

$$Q_{E,max} = 2.2(VP_S - VP_A)hA \qquad (6)$$

where

VP_S = saturated water vapor pressure of the skin node,
VP_A = water vapor pressure of air node,
h = convective heat transfer coefficient, and
A = surface area of the skin node.

Values for vapor pressure depend on temperature and relative humidity. There are published curves (e.g., Schmidt-Nielsen[8]) that plot the vapor pressure as a function of temperature for various relative humidities. If $Q_{E,i}$ exceeds $Q_{E,max}$ for any node, then $Q_{E,i}$ is set equal to $Q_{E,max}$.

Set point temperatures. For modeling purposes, the set point temperatures, T_{set}, contained in Equations (4) and (5) represent the temperatures the thermoregulation system attempts to maintain. For a nude, resting man, a thermal neutral environment implies an ambient temperature (T_{air}) of 30°C and 30% relative humidity (RH). Set point temperatures can then be determined for these conditions by solving Equation (1) with the blood flow set at basal levels and no sweating, that is, the controlling system (DILAT, STRIC, and SWEAT) is not activated. However, thermal neutral conditions for a squirrel monkey are not so well defined. Cutaneous tail vasodilation occurs at approximately 25°C,[12] while the foot, and presumably the rest of the body, vasodilates at an ambient temperature of 30°C. The situation is further complicated because evaporative heat loss to the environment remains at basal levels until $T_{air} \approx 32$°C, then active sweating on the feet and hands ensues. Thus, because vasodilation is initiated at two different T_{air}'s and sweating at yet another T_{air}, three sets of T_{set} are required.

The set point temperatures for the squirrel monkey model are determined by the following sequence. First, Equation (1) is solved with all blood flows at basal levels with T_{air} and RH being fixed at 25°C and 50%, respectively. Under these conditions the controlling system is not activated. The resultant steady-state temperatures for the tail skin nodes are designated as set point temperatures for the tail (see Equation 4). Next, the same procedure is utilized to calculate T_{set} for the rest of the skin nodes, except T_{air} is assigned a value of 30°C and cutaneous tail vasodilation is allowed. Finally, T_{set} associated with Equation (5) is determined by solving Equation (1) a third time, but for $T_{air} = 32$°C. This time, total skin vasodilation is permitted.

Controlling system

Physical or engineering models of the controller system incorporate these set point or reference temperatures and a deviation between the set point temperature and the actual temperature represents an error signal. The magnitude of the response is directly related to the size of the error signal. The relationship between the error signal and thermal response (vasoconstriction, vasodilation, and sweating) can be approximated by a general controller expression

$$\text{CONTROL} = A(T_H - T_{H,set}) + B \sum D_i(T_i - T_{i,set}). \quad (7)$$

The term $(T_H - T_{H,set})$ represents the difference between brain temperature and its set point temperature. It accounts for the thermoreceptors in the hypothalamus. The second quantity in the expression represents the total integrated difference between the skin temperature and the skin set point temperature, where the summation is across all skin nodes. Thus, the error signal is determined according to the values for $(T_H - T_{H,set})$ and $(T_i - T_{i,set})$: positive values are warm receptor outputs and negative values imply cold receptor outputs. This controller equation is used to affect the vasomotor response through the DILAT and STRIC commands in Equation (4) and the sweating response via the SWEAT command in Equation (5). If the error signal is positive, then the DILAT and SWEAT commands are activated. A negative error signal implies that STRIC is activated; however, the value that is substituted into Equation (4) is the magnitude of the error signal.

The quantities A and B are empirical constants and are designated as control coefficients. For the controller commands DILAT and SWEAT, these constants have been scaled to properly reflect the surface area of the

squirrel monkey vis-a-vis that of a human. Values for the controller command for vasconstriction (STRIC) are the same as in Stolwijk's human model.[14] No scaling is required because these coefficients are nondimensional (see Stolwijk,[15] for further details). Table 2 contains values for the controller coefficients.

Values for D, the fraction of the skin receptors associated with each node, are determined by assuming a uniform distribution over the body. Thus, the value of D for node i would be determined by dividing the surface area associated with node i by the total surface area of the body, exclusive of the tail. For the tail the same procedure is employed, except the surface area of the node is divided by the surface area of the tail.

NUMERICAL RESULTS

To demonstrate the model's ability to calculate the squirrel monkey's thermoregulatory profile for various environmental conditions, numerical results will be presented for ambient air temperatures of 20 to 37°C, a constant relative humidity of 50%, and still air (wind velocity < 0.1 m/s). The program is executed until thermal steady state conditions are reached for a given environmental condition. The iteration time step between calculations is 4.7 s, as based on the smallest block in the model. The program is terminated when the difference in temperature for consecutive iteration ≤0.001°C for all the nodes. The set point temperatures are used as the initial temperature values for all the nodes. Whenever possible, numerical values are compared with experimental data.[12]

Figure 4 shows calculated results for the rectal and mean skin temperatures versus ambient air temperature in the range of 20°C to 37°C. The rectal temperature is determined from a core node in the lower trunk region that is about 6 cm from the surface. Mean skin temperature represents the average of all the skin node temperatures. Also, superimposed on the graph are experimental data.[12] Note that the calculated rectal temperature remains relatively constant with values between 37°C and 40°C, whereas the mean skin temperature had an approximate linear relationship that showed a decrease of around 0.5°C for every 1°C drop in the air temperature. For both cases, there is fairly good agreement between calculation and measurement, especially for ambient air temperatures in excess of 26°C. The reason(s) for the larger discrepancy below 26°C is not clear. Interestingly, Stolwijk[14] found

Table 2. Controller coefficients

Controller command	A	B
1. SWEAT	7.4	0.7
2. STRIC	5.5	5.0
3. DILAT		
a. Body	1.9	0.1
b. Tail	0.3	0.02

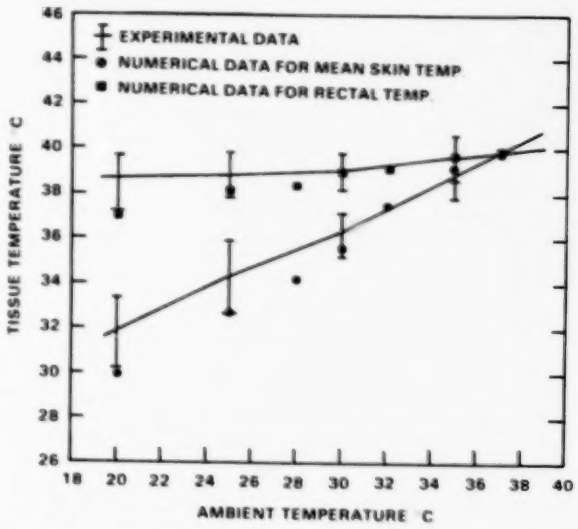
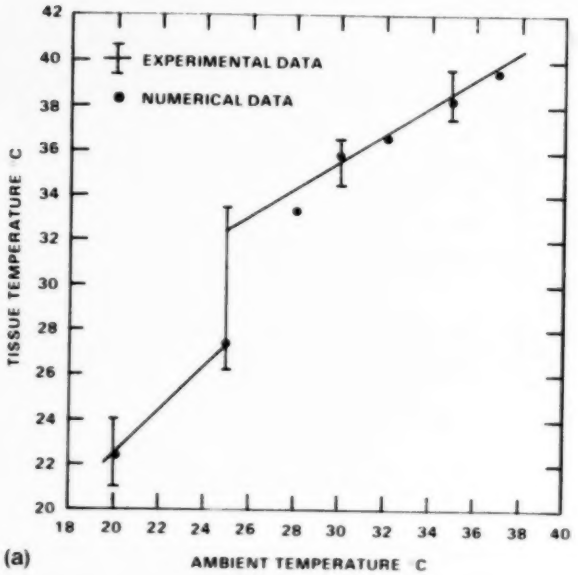


Fig. 4. A comparison of calculated and measured[12] rectal and mean skin temperatures in a squirrel monkey versus ambient temperature. The error bars represent the range of the experimental values. RH = 50% and air velocity = 0.1 m/s for the calculations.

that the prediction accuracy of the human model is diminished at colder temperatures. In fact, another model [Gordon *et al.*[4]] indicates that a heat flux control signal, which is not contained in the Stolwijk model, may be required to achieve enhanced prediction accuracy for colder environments. Another possibility is that the model's larger than normal surface area in relation to body weight may produce somewhat larger heat losses at lower temperatures.

The role of the tail and foot in thermoregulaton is demonstrated by the plots contained in Figure 5a and 5b, respectively. Again, the experimental data is taken from Stitt and Hardy.[12] The abrupt increase in the tail skin temperature at T_{air} = 25°C demonstrates that the tail has undergone cutaneous vasodilation at this point. A similar situation occurs for the foot, except the vasodilaton threshold is higher (T_{air} = 30°C). Thus, the tail appears to be of primary importance for vasomotor thermoregulation of the animal when the ambient temperature range is between 25°C to 30°C. In other words, by regulating the amount of cutaneous blood supply to the tail, the animal can regulate the amount of heat loss from the tail's surface. Above T_{air} = 30°C, vasomotor thermoregulation is achieved by both the tail and feet.

The sudden increase in skin blood flow at the vasodilation threshold ambient temperatures (T_{air} = 25°C, 30°C) is apparent from the data shown in Figure 6. These data represent steady-state blood flow levels as determined via Equation 4; the data have been normalized with respect to the basal blood flow rate. Even though regional as well as whole body skin blood flows can exhibit marked increases, the total blood flow (solid line) does not show



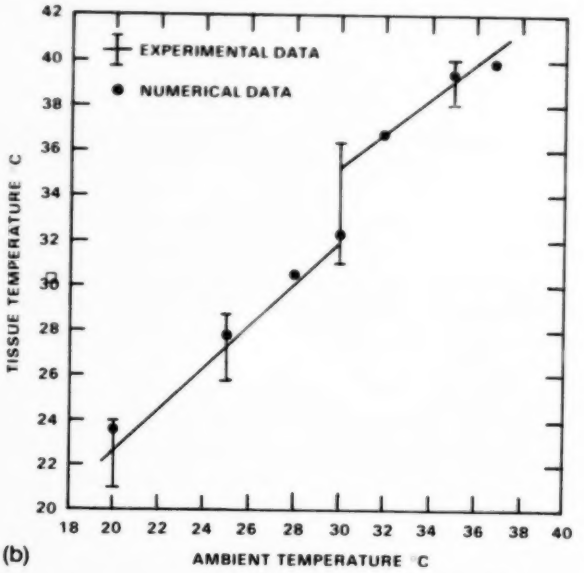


Fig. 5. A comparison of calculated and measured[12] skin temperature versus ambient temperature. The error bars represent the range of the experimental values, RH = 50% and air velocity = 0.1 m/s for the calculations. (a) Tail skin temperature. (b) Footskin temperature.

much increase until the ambient temperautre is well in excess of 30°C, resulting because skin blood supply is a rather small percentage of the total blood pool. Further, it is important to observe that cutaneous vasoconstriction (normalized flows less than 1) occurs for ambient temperatures below the threshold levels. These reduced skin blood flows result in reduced heat loss through the skin.

Figure 7 contains a normalized graph of the total evaporative heat loss versus ambient temperature. Values for

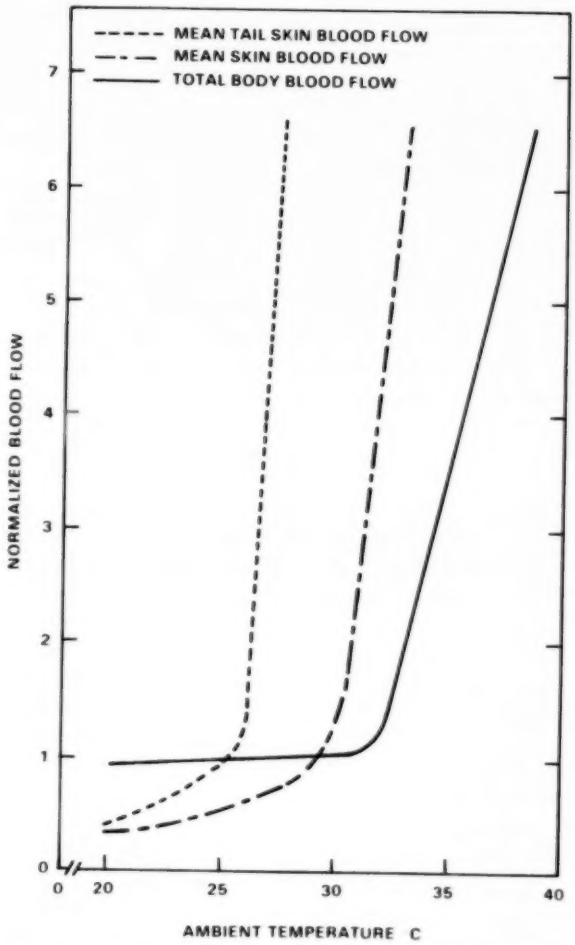


Fig. 6. A normalized plot of mean tail skin, mean body skin, and total body blood flow versus ambient temperature. RH = 50% and air velocity = 0.1 m/s for the calculations.

the calculated curve emanate from Equation (5), whereas the experimental data are taken from Stitt and Hardy.[12] Clearly, the comparison between the computed values and the experimental values is good. At T_{air} = 34°C the sweating rate begins to increase and at T_{air} = 37°C, Q_E is over 4 times the basal level. Note, that both the calculated and measured data do not include respiratory heat loss. At ambient temperatures where sweating occurs, the respiratory heat loss remains at basal levels and consequently contributes minimally to the total evaporative heat loss term.

Selected temperature and thermoregulatory responses, as a function of time, were calculated as T_{air} changed from 30 to 35°C (Figure 8a) and to 25°C (Figure 8B). At t = 0, the calculations are initiated with tissue temperatures equilibrated for T_{air} = 30°C. For the T_{air} = 35°C case, the skin temperatures quickly increase but the rectal, hypothalmic, and blood temperatures decrease slightly from their initial values and then increase. The initial decrease

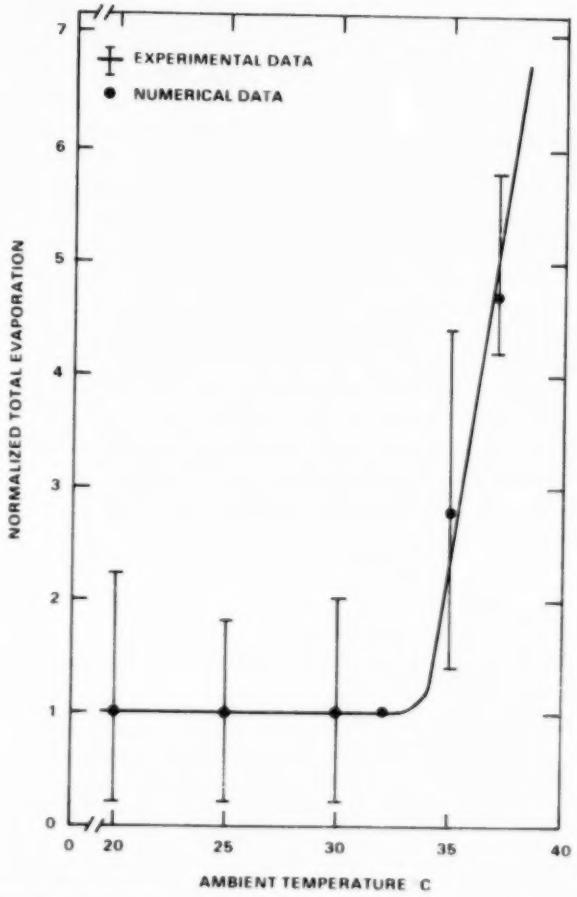


Fig. 7. A comparison of calculated measured[12] evaporative heat losses versus ambient temperature. The error bars represent the range of the experimental values. RH = 50% and air velocity = 0.1 m/s for the calculations.

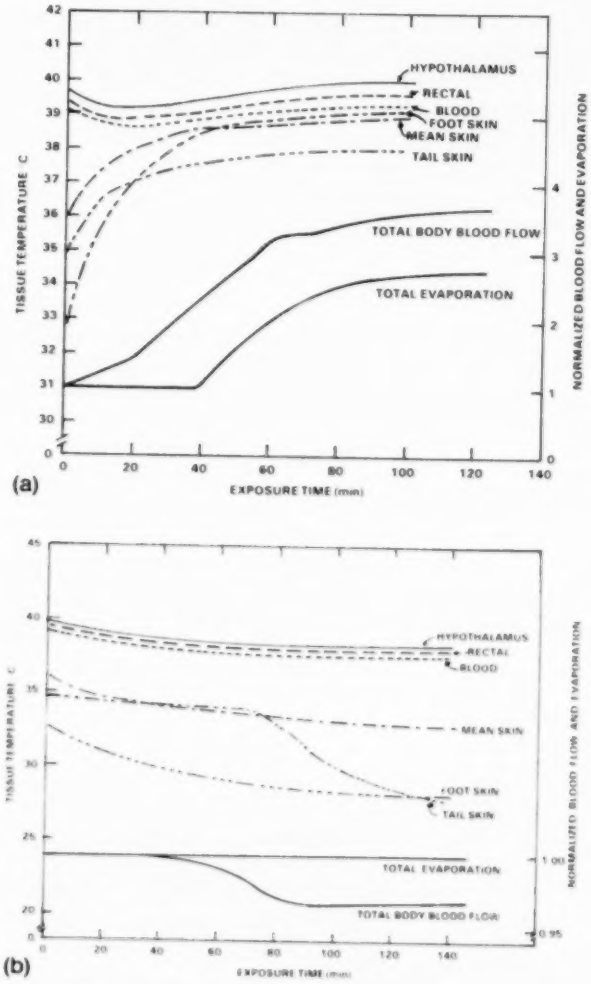


Fig. 8. Selected temperature and thermoregulatory responses as a function of exposure time. RH = 50%, and air velocity = 0.1 m/s. (a) T_{air} = 35°C. (b) T_{air} = 25°C.

in internal temperatures is probably due to the onset of skin vasodilation. The steady-state values for the internal (rectal, blood, and hypothalmic) temperatures are somewhat elevated over the values for T_{air} = 30°C, but skin temperatures, especially the foot, are significantly larger than initial values. Note, the concomitant increase in total blood flow and evaporative heat loss (sweating). When T_{air} = 25°C, there is a gradual decrease in all the temperatures, except the tail skin temperature. At about 70 min after the start of exposure, there is a rapid drop in tail skin temperature; this effect occurs as a result of cutaneous vasoconstriction in the tail. The total blood flow decreases by approximately 3 percent, as shown by the bottom curve of Figure 8b.

DISCUSSION

The main objective of this paper was to demonstrate that a thermoregulatory model of a squirrel monkey can be achieved by the adaptation of a human model, the utilization of existing physiological data, and plausible assumptions. The utility of a squirrel monkey model is based on the premise that certain experimental thermoregulatory studies on the response of humans to physical insults (e.g. RF energy) may be difficult or impossible to undertake as a result of possible risk to the subjects. It was substantiated that reasonable agreement between calculated and available measured data could be obtained. For example, calculated steady state temperature values of mean skin and rectal temperatures were essentially within the variation of experimental data over an ambient temperature range of 20 to 37°C. Likewise, both the calculated tail and foot temperatures agreed with measured values; even the abrupt temperature increases due to cutaneous foot and tail vasodilation were accurately simulated.

To indicate the sensitivity of the computed results to changes in key parameters such as the blood flow rate and metabolic rate, variations in computed results were compared with parameter value changes. It was found that the calculated tissue temperatures were relatively insensitive to changes in blood flow rate, but were fairly sensitive to metabolic rate changes. For example, with the ambient air temperature 30°C, if the basal blood flow is increased by a factor of 2, the skin temperature change is minuscle. Core temperature changes, with the exception of the head, were also small. The head core temperature decreased approximately 0.75°C. When the basal metabolic rate is changed 20%, core temperature changes are on the order of 1.5°C. Skin temperature changes are around 1°C. Thus, the proper distribution of metabolic heat sources in the model is crucial to achieve accurate results. However, a better distribution than presented here will have to await experimental data for the various tissues and organs of the monkey.

The computer memory requirement to operate the code is on the order of 3,000 K bytes. This model is executed on an IBM 3081 computer, and approximately 30 min of central processing time (CPU) are required to achieve steady-state thermal conditions. Because of the large input data set, the manual entering of this information into the computer is laborious. The three-dimensional spatial quantification of all the blocks associated with the model is also difficult because only two-dimensional views are convenient when the data is generated by hand. Three-dimensional graphics systems are available for automating these tasks, but substantial software development may be required to tailor a graphics system for this application.

Finally, based on these results we conclude that the model has been reasonably verified for changing environmental temperatures. This conclusion provides a confident basis on which to proceed with the utilization of this model when RF energy is included as an additional heat source.

REFERENCES

1. Altman, P.L., Dittmer, D.S.: *Biological Handbooks: Respiration and Circulation.* Bethesda, MD., Federation of the American Society for Experimental Biology. 1971, pp. 327–331.
2. Cena, K., Clark, J.A.: Thermal insulation of animal coats and human clothing. *Phys. Med. Biol.* **23:** 565–591, 1978.
3. Gordon, C.J.: A review of terms for regulated vs. forced neurochemical-induced changes in body temperature. *Life Sci.* **32:** 1285–1295, 1983.
4. Gordon, R.G., Roemer, R.B., Horvath, S.M.: A mathematical model of the human temperature regulatory system-transient cold response. *IEEE Trans. Biomed. Eng.* **BME-23:** 434–444, 1976.
5. Holman, J.P.: *Heat Transfer.* 4th edition. NY, McGraw-Hill. 1981, p. 131.
6. Hwang, C.L., Konz, S.A.: Mathematical models of thermal regulation. *IEEE Trans. Biomed. Eng.* **BME-27:** 309–325, 1977.
7. Rand, R.P., Burton, A.C., Ing, T.: The tail of the rat, in temperature regulation and acclimatization. *Can. J. Physiol. Pharmacol.* **43:** 257–267, 1965.
8. Schmidt-Nielsen, K.: *Animal Physiology: Adaptation and Environment.* 2nd edition. Cambridge, Cambridge University Press. 1979, p. 308.
9. Shepherd, J.T., Abboud, F.M.: *Handbook of Physiology: The Cardiovascular System.* Vol III, *Peripheral Circulation.* Part 2. Baltimore, MD, Waverly. 1983, pp. 967–1023.
10. Spiegel, R.J.: A review of numerical models for predicting the energy deposition and resultant thermal response of humans exposed to electromagnetic fields. *IEEE Trans. Microwave Theory Tech.* **MTT-32:** 730–746, 1984.
11. Stitt, J.T., Adair, E.R., Stolwijk, A.J.: The relation between behavior and physiology in the thermoregulatory response of the squirrel monkey. *J. Physiol. Paris* **63:** 424–427, 1970.
12. Stitt, J.T., Hardy, J.D.: Thermoregulation in the squirrel monkey (Saimiri scriureus). *J. App. Physiol.* **31:** 48–54, 1971.
13. Stitt, J.T., Hardy, J.D., Nadel, E.R.: Surface area of the squirrel monkey in relation to body weight. *J. App. Physiol.* **31:** 140–141, 1971.
14. Stolwijk, J.A.J.: A mathematical model of physiological temperature regulation in man. *NASA CR-1855 (NTIS N71-33401).* Washington, DC, 1971.
15. Stolwijk, J.A.J.: Expansion of a mathematical model of thermoregulation to include high metabolic rates. *NASA CR-102192 (NTIS NTD-19831).* Washington, DC, 1969.

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